Concrete building design optimization for reduced life-cycle costs and environmental impacts

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PROBLEM

Decisions made at early stages of the building design process can have a large influence on the environmental performance and financial costs of a building. One of the best ways to discover preferable designs is to analyze and compare many different alternatives. However, due to time and data requirements, assessments of a building's environmental impacts and costs can be time-consuming and difficult to perform early on. Even with streamlined tools, such as the CSHub-developed Building Attribute to Impact Algorithm (BAIA), it can still be difficult to minimize life time impacts and costs through manual comparisons of alternatives. Combining tools like BAIA with optimization methods can help identify the best ranges for key design parameters.

APPROACH

Life cycle cost estimates have been added to BAIA to account for the material and labor costs of all components included in the scope of the environmental impact calculations. These costs include the foundation, exterior walls, windows, interior walls, floors, ceiling, and roof, but exclude interior finishes, appliances, electrical/lighting systems, and plumbing. Also included in the costs are an estimate of the HVAC system cost and the estimated cost of energy consumption over the lifetime of the building, which takes fuel type (electricity or gas) and price variations by state into account.

A genetic algorithm, which is an optimization method inspired by the concept of natural selection, was applied to BAIA to minimize life cycle impacts and costs of two 2,400-square-foot single-family residential ICF buildings in two different locations: Chicago, Illinois, and Phoenix, Arizona. The algorithm starts with a random set of designs (within ranges set by the user), then picks a subset of the designs with the lowest BAIA-calculated costs and impacts to use as the "parents" in the next generation. Each design in the following generation is created by randomly combining design parameters from two randomly-selected parents, and the optimization continues until the mean impacts and costs have similar values for several consecutive generations. For this analysis, the optimization ran for 40 generations. The resulting designs were then

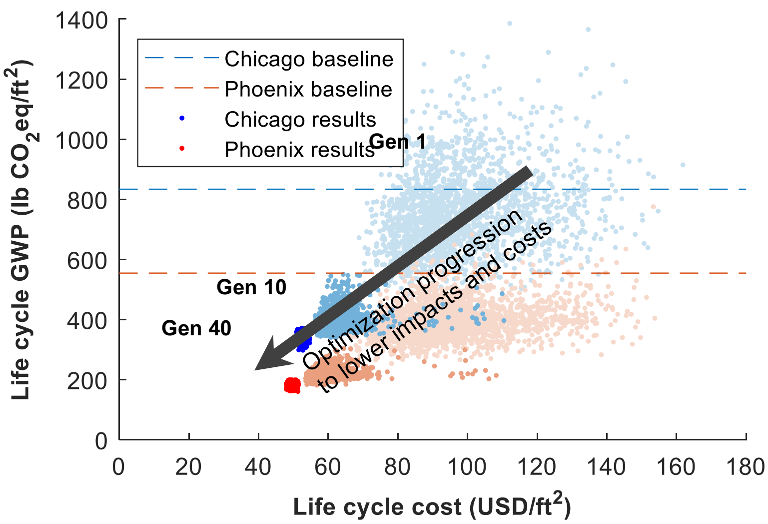

Figure 1 – Genetic optimization, showing reduction in impacts and costs from 1st to 40th generations (darker colors indicate later generations), as well as baseline GWP values from a 2011 CSHub study.

WHY DOES THIS RESEARCH MATTER?

- Optimum designs are context-dependent, and the climate of the building location must be considered.
- This research demonstrates that it is possible to reduce both life cycle costs and life cycle environmental impacts of early design decisions by using optimization with streamlined analysis methods.
- Using optimization methods early in the design process can provide building practitioners with more information about preferable options for key design parameters in a given climate.

This research was carried out by the CSHub@MIT with sponsorship provided by the Portland Cement Association and the Ready Mixed Concrete Research & Education Foundation. CSHub@MIT is solely responsible for content. Authors: J. Hester, J. Gregory, and R. Kirchain

analyzed to extract information about the optimum design features, as well as the improvements in life cycle costs and impacts over the course of the optimization. The life cycle impacts were also compared to values from buildings studied in a 2011 CSHub report.

FINDINGS

After 40 generations of optimization with the genetic algorithm (see Figure 1, page 1), the mean life cycle impacts for the two buildings (one sited in Chicago and the other in Phoenix) were reduced by approximately 55%, and the mean life cycle costs by approximately 47% as compared to the mean values seen in the initial generations (see Table 1, below). The global warming potential values were 82% and 85% lower than the baseline values from the 2011 study (indicated by dotted lines in Figure 1).

Some of the design changes that led to improvements for the buildings we studied are highlighted in Table 2. To summarize those changes: both buildings demonstrated substantially higher R-values for the roof (the R-value measures the level of insulation). The Chicago building saw slightly lower wall R-value and slightly higher foundation R-value, while the Phoenix building saw a much lower wall R-value and moderately lower foundation R-value. Additionally, the Phoenix building had a reduced solar heat gain coefficient and the Chicago building had a larger coefficient, meaning that less heat was allowed through the windows in Phoenix and more was allowed through in Chicago.

Table 1 – Comparison of life-cycle impacts and costs between initial and optimized BAIA designs, with percentage change from the first generation to the final generation. Darker shading indicates greater improvement from initial values.

	Initial BAIA design		**Optimized BAIA design**		**Change from initial design**	
	Chicago	Phoenix	Chicago	Phoenix	Chicago	Phoenix
Life-cycle GWP (lb CO_2 eq/ft^2)	344.7	179.6	153.8	82.3	-55%	-54%
Life-cycle Cost (USD/ft^2)	98.7	96.1	52.6	49.7	-47%	-48%

Table 2 – Average initial and optimized values for subset of key design parameters of Chicago and Phoenix buildings, with percentage change from first generation to final generation. Darker shading indicates greater deviation from initial values.

	Initial BAIA design	**Optimized BAIA design**		**Change from initial design**	
		Chicago	Phoenix	Chicago	Phoenix
Wall R-value*	35	32	19	-7%	-45%
Foundation R-value*	16	22	11	36%	-34%
Attic R-value*	33	46	51	41%	56%
Window R-value*	2.6	2.7	2.7	4%	4%
Window-to-wall ratio	0.25	0.11	0.10	-58%	-59%
Window SHGC	0.34	0.50	0.22	45%	-37%

*R-values expressed in hr-ft^2-F/Btu

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